

# PERFORMANCE ENHANCEMENT IN MULTIRATE WI-FI NETWORKS

Olga TARASYUK, Anatoliy GORBENKO

National Aerospace University, Department of Computer Systems and Networks  
Ukraine

e-mail: O.Tarasyuk@csn.chai.edu, A.Gorbenko@csn.chai.edu

## Abstract

*In the paper we address a problem of throughput unfairness inherent in the very nature of multirate Wi-Fi networks employing CSMA/CA mechanism. This unfairness exhibits itself through the fact that slow clients consume more airtime to transfer a given amount of data, leaving less airtime for fast clients. The paper introduces analytical models allowing estimating a fair contention window (CW) size to be used by each station depending on a ratio between station's data rates or the airtime consumed by each station. We also analyze PHY and MAC overheads that significantly degrade performance of high data rate stations and investigate how different performance enhancement techniques affect average delay of getting access to the media.*

**Keywords:** *multirate wireless networks, throughput, contention window, adaptation*

## 1 INTRODUCTION

Throughput unfairness in Wi-Fi networks is a well known issue caused by unfair airtime distribution between stations with different data rates [1]. Slow stations occupy more airtime to transfer the same amount of data. This significantly degrades performance of high-speed stations and decreases the overall network throughput. The situation is happened because of a coexistence of heterogeneous 802.11 Wi-Fi devices of  $a/b/g$  and  $n$  types. Besides, some of stations can use slower link speed when they deliver a weak signal to the access point (AP) because of the large distance between them or due to high interference level.

In [2] we demonstrated both experimentally and theoretically that a data rate of the slowest station mostly determines the throughput of all other stations, even if their link speeds are much higher. This finding is in line with some earlier studies [3, 4]. To address the problem of airtime unfairness some vendors implement their proprietary solutions. Undoubtedly, these solutions are extremely sophisticated and details of their operation are not generally public knowledge.

In our previous work [2] we proposed an analytical model estimating Wi-Fi throughput with regards to airtime consumption unfairness and also discussed possible approaches of how to deal with performance degradation by granting a priority access to the medium to fast stations.

These approaches are based on two ideas:

(i) faster stations should be granted a right to send a frame of a bigger size or more frames than one when they get access to the medium;

(ii) faster stations should get a higher chance to access the medium (i.e. get more transmission opportunities) than slower ones. This can be achieved via scaling down their contention windows or by scaling up contention windows used by slow stations.

The last approach is similar to QoS techniques introduced by IEEE802.11e standard to protect high priority data from low priority one [5]. A station wishing to send high priority traffic should wait a bit less before it sends its frame, on average, than a station sending low priority traffic. This is achieved via using a shorter arbitration inter-frame space (AIFS), a smaller size of a contention window (CW) and a bigger transmit opportunity period (TXOP) for higher priority frames. As a result high-priority traffic has a higher chance of being sent than low-priority traffic.

There have been several studies enhancing distributed coordination function and improving performance of Wi-Fi networks by controlling CW and TXOP parameters [6–9]. Even though these works are important for facilitating the unfairness issue and improving CSMA/CA performance for high-density networks, they are rather heuristic and provide only suboptimal solutions mainly based on simulation results. Existing works do not provide an explicit and lightweight model allowing to fairly set up stations contention windows depending on difference in data rates used by them. Moreover, some of the offered solutions like [10, 11] where researches proposed an idea that the ratio of the contention windows should be equal to the ratio of stations respective rates, suffer from obvious shortcomings.

In the paper we discuss a scenario when data sent by high-data rate stations need to be protected from other data of the same class sent by slow stations. We propose mathematical models estimating a fair size of stations contention windows taking into account station data rates and also PHY and MAC layers overheads. Though, most of researches mainly focus on improving network throughput, it is also important to account how throughput enhancement affects network delay and to understand a tradeoff between them.

The rest of the paper is organized as follows. In the second section we perform a combinatorial analysis of probability of getting access to the medium for stations using different contention window settings. In the third section we present analytical models estimating a fair contention window size to be used by slower stations depending on a ratio between stations data rates. The fourth section discusses PHY and MAC layers overheads and their effect on the network performance. Finally, in the fifth section we analyze station's delay of getting access to the medium.

## 2 COMBINATORIAL ANALYSIS OF PROBABILITY OF GETTING ACCESS TO THE MEDIUM DEPENDING ON CONTENTION WINDOW SETTINGS

Providing fair airtime distribution requires setting up stations contention windows taking into account a ratio between data rates they use so that faster stations have a higher chance to access the medium. It means that, for instance, in case of two-station network configuration a station with the higher data rate has to get more transmission opportunities proportionally to the ratio of data rates of fast and slow stations. However, such a straightforward proportion cannot be established between stations data rates and their contention windows as the actual backoff is randomly selected from a range  $[0..CW]$ . This concept is a core difference between our work and studies [10, 11] where a random nature of the backoff timer had not been taken into consideration by them.

To understand a correlation between the sizes of stations' contention windows and a number of transmission opportunities they get, a combinatorial analysis of stations probabilities to access medium has been performed. Let us assume that two stations use contention windows  $CW_1$  and  $CW_2$  of different size. For instance, if  $CW_1=2$  and  $CW_2=3$  the first station chooses a random backoff between 0 and 2 (inclusively) while the second station chooses between 0 and 3. In this case the first station gets six favorable outcomes (six logical disjunctions) to transmit data when:

$$\begin{aligned} & (backoff_1=0 \text{ AND } backoff_2=1) \text{ OR } (backoff_1=0 \text{ AND } backoff_2=2) \text{ OR} \\ & \text{OR } (backoff_1=0 \text{ AND } backoff_2=3) \text{ OR } (backoff_1=1 \text{ AND } backoff_2=2) \text{ OR} \\ & \text{OR } (backoff_1=1 \text{ AND } backoff_2=3) \text{ OR } (backoff_1=2 \text{ AND } backoff_2=3). \end{aligned}$$

The second station gets the only three transmission opportunities, provided that stations backoffs are as follow:

$$\begin{aligned} & (backoff_1=1 \text{ AND } backoff_2=0) \text{ OR } (backoff_1=2 \text{ AND } backoff_2=0) \text{ OR} \\ & \text{OR } (backoff_1=2 \text{ AND } backoff_2=1). \end{aligned}$$

Combinations when two stations randomly select the same backoffs ( $backoff_1=0$ ,  $backoff_2=0$ ;  $backoff_1=1$ ,  $backoff_2=1$ ;  $backoff_1=2$ ,  $backoff_2=2$ ) cause a collision and a subsequent retry using a binary exponential backoff. Thus, we can take them out of consideration. As a result, a combinatorial probability of getting access to the medium for the first station is equal to  $6/9=0.66(6)$  whereas for the second station it equals to  $3/9=0.33(3)$ . Table 1 presents several other results of transmission opportunities combinatorial analysis for each of two stations with different contention window settings.

For example, if  $CW_1=2$  and  $CW_2=3$  the first station gets twice as many opportunities to transmit data that would be fare on condition that the data rate used by the second station is twice as less than the data rate of the first station (i.e. when the second station consumes twice as much airtime to transmit the same amount of data).

**Table 1** Probabilities of Getting Access to the Medium Depending on Stations Contention Window Settings

Medium access parameters \ Contention window settings	1st case	2nd case	3rd case
	$CW_1 = 2$ $CW_2 = 3$	$CW_1 = 2$ $CW_2 = 4$	$CW_1 = 3$ $CW_2 = 4$
Number of transmission opportunities available for the first station $q_1$	6	9	10
Number of transmission opportunities available for the second station $q_2$	3	3	6
Combinatorial probability of getting access to the medium for the first station, $p_1 = q_1 / (q_1 + q_2)$	0.66(6)	0.75	0.625
Combinatorial probability of getting access to the medium for the second station, $p_2 = q_2 / (q_1 + q_2)$	0.33(3)	0.25	0.375
A ratio between stations transmission opportunities, $q_1/q_2 = p_1/p_2$	2	3	1.66(6)

### 3 A MODEL OF A FAIR CONTENTION WINDOW

#### 3.1 Two-station Network Configuration

Particular results of a combinatorial analysis allowed us to derive a number of opportunities of getting access to the medium for the second station (with a wider contention window) as a  $k$ -combination of  $n$ , where  $k=2$  and  $n$  is the incremented size of a contention window used by the first station:

$$q_2 = \binom{CW_1 + 1}{2}.$$

A number of opportunities of getting access to the medium for the first station with the narrower contention window can be deduced as:

$$q_1 = \binom{CW_2 + 1}{2} - \binom{CW_2 - CW_1}{2}, \text{ provided that } CW_2 \geq CW_1.$$

A problem of ensuring a fair airtime distribution consists in choosing such contention window size for each station so that a ratio between stations transmission opportunities be equal to a ratio  $k$  between their data rates:

$$\frac{q_1}{q_2} = \frac{V_1}{V_2} = k, \quad (1)$$

where  $V_1$  – is a data rate of the faster station,  $V_2$  – is a data rate of the slower station,  $V_1 \geq V_2$ .

In case of two stations we can define the following equality, substituting  $n$  for  $(CW_1+1)$  and  $m$  for  $(CW_2+1)$ :

$$k \cdot \binom{n}{2} = \binom{m}{2} - \binom{m-n}{2}, \quad (2)$$

Knowing that  $\binom{n}{2} = \frac{n^2 - n}{2}$  we can rewrite (2) as:

$$k \cdot \frac{n^2 - n}{2} = \frac{m^2 - m}{2} - \frac{(m-n)^2 - (m-n)}{2} \quad (3)$$

Solving the equation (2) for  $m$  (which is an incremented contention window of the slower station  $CW_2$ ) we obtain the following:

$$m = \frac{k(n-1) + n + 1}{2}.$$

Finally, substituting  $(CW_1+1)$  for  $n$ ,  $(CW_2+1)$  for  $m$  and  $\frac{V_1}{V_2}$  for  $k$  we get:

$$CW_2 = \frac{k \cdot CW_1 + CW_1}{2} = \frac{1}{2} \cdot \left( \frac{V_1 \cdot CW_1}{V_2} + CW_1 \right). \quad (4)$$

The equation (4) can be used to set up a contention window of a slower station so that a fair airtime distribution is provided. It takes into account a size of the contention window used by a faster station and a ratio between stations link speeds.

Table 2 provides some numerical examples of estimation a fair contention window to be used by a slower station in case of two-station network configuration. Fast and slow stations use data rates denoted as  $V_1$  and  $V_2$  respectively ( $V_1 \geq V_2$ ).

If the size of contention window estimated with the help of (3) is a fractional number it should obviously be rounded off to the closest integer value (put in parentheses).

Correctness of the proposed model is verified by following reasonings.

Firstly, when both stations use the same data rate they should use contention windows of the same size, which is confirmed by the last row of Table 2. Secondly, provided that  $CW_1=3$ ,  $V_1=300$  Mbit/s and  $V_2=180$  Mbit/s (i.e.  $V_1/V_2=1.66(6)$ ), the second station should set up its contention window to 4 (the ninth row of the 1<sup>st</sup> case in Table 2). This is exactly in line with one of the cases we examined in previous section via a combinatorial analysis. Readers can follow the similar reasoning to double check all the rest results given in Table 2 by them.

**Table 2** Probability of Getting Access to the Medium Depending on Stations Contention Window Settings

$V_1$ Mbit/s	$V_2$ Mbit/s	1st case		2nd case		3rd case	
		<i>Given</i> $CW_1$	<i>Estimated</i> $CW_2$	<i>Given</i> $CW_1$	<i>Estimated</i> $CW_2$	<i>Given</i> $CW_1$	<i>Estimated</i> $CW_2$
300	15	3	31.5 (32)	7	73.5 (74)	15	157.5 (158)
300	30	3	16.5 (17)	7	38.5 (39)	15	82.5 (83)
300	45	3	11.5 (12)	7	26.83 (27)	15	57.5 (58)
300	60	3	9	7	21	15	45
300	90	3	6.5 (7)	7	15.17 (15)	15	32.5 (33)
300	120	3	5.25 (5)	7	12.25 (12)	15	26.25 (26)
300	135	3	4.83 (5)	7	11.28 (11)	15	24.17 (24)
300	150	3	4.5 (5)	7	10.5 (11)	15	22.5 (23)
300	180	3	4	7	9.33 (9)	15	20
300	240	3	3.38 (3)	7	7.88 (8)	15	16.88 (17)
300	270	3	3.17 (3)	7	7.39 (7)	15	15.83 (16)
300	300	3	3	7	7	15	15

### 3.2 Three-station Network Configuration

Let us consider a three-station network configuration when stations contention windows are  $CW_1=2$ ,  $CW_2=3$  and  $CW_3=4$ . The combinatorial analysis shows that a number of favorable backoffs combinations allowing each station to access the medium can be estimated as:

$$q_1 = CW_2 CW_3 + (CW_2 - 1)(CW_3 - 1) + (CW_2 - 2)(CW_3 - 2) = 3 \cdot 4 + 2 \cdot 3 + 1 \cdot 2 = 20$$

$$q_2 = CW_1 CW_3 + (CW_1 - 1)(CW_3 - 1) = 2 \cdot 4 + 1 \cdot 3 = 11$$

$$q_3 = CW_1 CW_2 + (CW_1 - 1)(CW_2 - 1) = 2 \cdot 3 + 1 \cdot 2 = 8$$

In general case we can define the following:

$$q_1 = \sum_{i=0}^{CW_1} (CW_2 - i)(CW_3 - i), \quad (5)$$

$$q_2 = \sum_{i=0}^{CW_1-1} (CW_1 - i)(CW_3 - i), \quad (6)$$

$$q_3 = \sum_{i=0}^{CW_1-1} (CW_1 - i)(CW_2 - i). \quad (7)$$

Fair airtime consumption assumes that the ratio of stations respective rates has to be equal to the ratio of transmission opportunities they get, so that:

$$\frac{V_1}{V_3} = \frac{q_1}{q_3}, \frac{V_1}{V_2} = \frac{q_1}{q_2}, \frac{V_2}{V_3} = \frac{q_2}{q_3}, \text{ where } V_1 \geq V_2 \geq V_3. \quad (8)$$

Thus, we have the three combined equalities allowing to estimate fare sizes of  $CW_2$  and  $CW_3$  to be used by the second and third stations if a size of  $CW_1$  is known:

$$\begin{aligned}\frac{V_1}{V_3} &= \frac{CW_1 + 2CW_1^2 - 3CW_1CW_2 - 3CW_1CW_3 + 6CW_2CW_3}{CW_1(3CW_2 - CW_1 + 1)}, \\ \frac{V_1}{V_2} &= \frac{CW_1 + 2CW_1^2 - 3CW_1CW_2 - 3CW_1CW_3 + 6CW_2CW_3}{CW_1(3CW_3 - CW_1 + 1)}, \\ \frac{V_2}{V_3} &= \frac{3CW_3 - CW_1 + 1}{3CW_2 - CW_1 + 1}.\end{aligned}$$

For instance, let us assume that  $V_1:V_2:V_3 = 5:3:1$  (e.g.  $V_1=300$ ,  $V_2=180$ ,  $V_3=60$ ) and  $CW_1=15$ . By solving the proposed set of equalities for  $CW_2$  and  $CW_3$  we can derive such values of contention windows to be used by the second and the third stations:  $CW_2 = 20.321=20$  and  $CW_3 = 51.63=52$ .

### 3.3 K-station Network Configuration

Employing a combinatorial analysis by analogy with the previous examples we can derive a set of general equations to be solved for obtaining fair sizes of stations contention windows. Thus, a number of favorable backoffs combinations the fastest station gets to transmit data is equal to:

$$q_1 = \sum_{i=0}^{CW_1} \prod_{j=2}^R (CW_j - i), \quad (9)$$

where  $CW_1$  is a default size of a contention window used by the fastest station;  $R$  is a total number of stations competing for the medium;  $CW_j$  is a contention window used by  $j$ -th station.

To estimate a number of transmission opportunities any slower station gets, we can use the following equation:

$$q_r = \sum_{i=0}^{CW_1-1} \frac{\prod_{j=1}^R (CW_j - i)}{(CW_r - i)}. \quad (10)$$

Finally, a system of equations (9) and (10) should be supplemented with:

$$\frac{V_r}{V_R} = \frac{q_r}{q_R}, \quad V_r \geq V_{r+1} \geq \dots \geq V_R, \quad r = 1 \dots R \quad (11)$$

where  $V_r$  is a data rate used by  $r$ -th station;  $V_R$  is a data rate of the slowest station in a network.

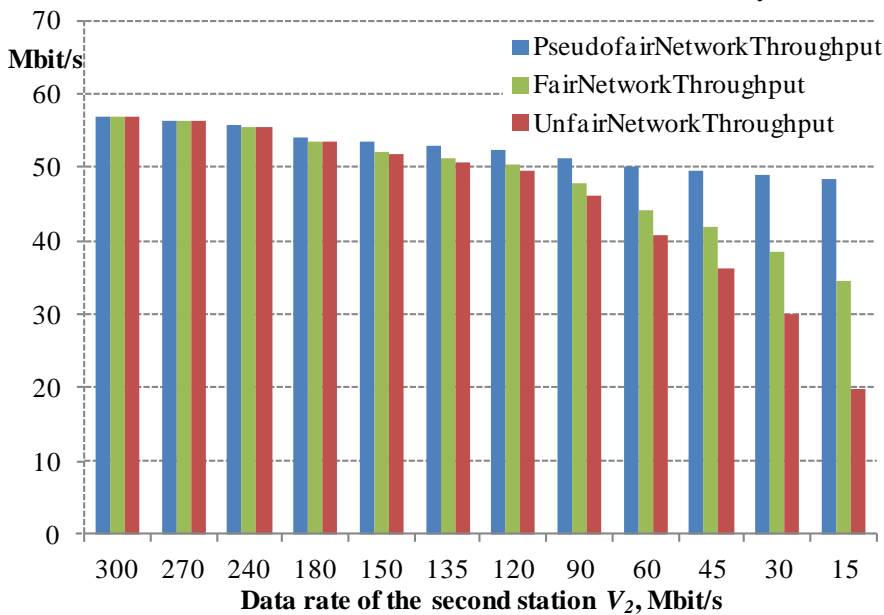
Solving a system of equations (9), (10) and (11) for  $CW_r$  allows to estimate a fair size of the contention window to be set by every station, provided that the fastest station uses a default contention window size and all stations know data rates of each other.

#### 4 ACCOUNTING PHY AND MAC LAYERS OVERHEADS

One of the main problems of modern Wi-Fi networks which reduce their effectiveness is protocol overheads at the physical and data link layers. Length of the PHY preamble, duration of DIFS interval and backoff time does not depend on the station data rate. In addition, each data frame should also be followed by the ACK response, separating by the SIFS interval [13]. As a result the real throughput available to the station connecting to the network at, for instance, 300 Mbit/s is only about 57 Mbps (assuming that the basic distributed coordination function is used and MPDU size is 1500 bytes). With the Greenfield preamble the overheads at PHY and MAC layers take about 170  $\mu$ s at data rate 300 Mbit/s and 195  $\mu$ s at 15 Mbit/s. As a result, transmitting a 1500 byte frame at the PHY data rate 300 Mbit/s is only about 5 times faster than at 15 Mbit/s (about 211  $\mu$ s versus 995  $\mu$ s). Using the mixed format preamble increases the overhead of the PHY preamble by 12  $\mu$ s.

This means that contention window settings should provide the probability of getting access to the media to be proportional to the ratio between the airtime consumed by each station rather than to the ratio between stations data rates. Thus, equalities (1), (8) and (11) need corrections correspondingly.

In this case, for instance, a relative ratio between probabilities of getting access to the media for two stations with data rates 300 Mbit/s and 15 Mbit/s should be equal to 4.7:1 (instead of 20:1). Figure 1 shows the real throughput for the two-station network depending on the data rate of the second station provided that the first station uses the constant data rate  $V_1=300$  Mbit/s. It takes into account overheads at PHY and MAC layers.



**Figure 1** Practically achieved network throughput for the two-station network provided that the first station uses the constant data rate  $V_1=300$  Mbit/s



Different histograms in Fig. 1 correspond to three cases when contention window settings provide the probability of getting access to the media to be:

1) proportional to the ratio between the airtime consumed by each station (*FairNetworkThroughput*). In this case different stations consume airtime equally;

2) proportional to the ratio between stations data rates without accounting PHY and MAC overheads (*PseudofairNetworkThroughput*). As a result, the throughput of the faster station as well as the overall network throughput is increased. Though, the throughput of the slower station is degraded due to a dominating role of PHY and MAC overheads in the airtime consumed by the faster station;

3) independent on the airtime consumed by each station and their data rates (*UnfairNetworkThroughput*). It decreases the overall network throughput and significantly degrades the throughput of a faster station due to airtime consumption unfairness [2].

## 5 AVERAGE DELAY OF GETTING ACCESS TO THE MEDIA

Most of the existing research works (e.g. [2–4, 13]) in wireless communications focus on improving network throughput rather than on reducing network delay and response time. New enhancements adopted in 802.11n standard like A-MPDU or A-MSDU aim to increase network effectiveness by aggregating protocol or service data units. The core idea of these techniques is to increase the payload (up to 8kB with A-MSDU and 64kB with A-MPDU) of a single transmission.

At the same time, frame aggregation, especially if it is employed by slow stations, can lead to the significant increase of the network delays. This causes a negative impact on latency-sensitive applications like VoIP. The basic Wi-Fi channel access cycle includes DIFS interval, backoff time, duration of the PHY preamble, MAC frame (MPDU header plus payload) transmission, SIFS interval and duration of ACK response. RTS/CTS frame exchange can also be employed in addition to protect station's transmissions from hidden nodes.

Table 3 presents the duration of each part of the basic Wi-Fi channel access cycle. The duration of only two parts of this cycle depends on station's data rate: MAC and ACK frames transmission. Moreover, to enhance reliability, the ACK frame is sent using a lower PHY data rate than the data frame.

If all stations use the same CW settings they compete for getting access the media on a fair basis (their probabilities of accessing the media are equal). In this case the average delay of getting access to the media is a half of a sum of transmission cycles of all stations. It is equal for all stations independently of data rates they use. Though in the general case we can derive that this delay depends on the probability of each station to get access to the media  $p_i$  and duration of stations transmission cycles:

$$T_{wait_i} = \frac{1}{2p_i} \sum_{j=1}^n p_j \cdot T_{cycle_j} . \quad (12)$$

**Table 3** Duration of the basic channel access cycle depending on the station data rate

Duration, us	Data rate, Mbit/s (MCS index)											
	300 (15)	270 (14)	240 (13)	180 (12)	150 (7)	135 (6)	120 (5)	90 (4)	60 (3)	45 (2)	30 (1)	15 (0)
DIFS	34											
Average back-off	$63 = (CW_{min} - 1) * T_{slot}/2$											
PHY preamble	28 (2 spatial streams)						24 28 (Greenfield mode, 1 spatial stream)					
MAC header time	0.9	1	1.2	1.5	1.8	2	2.3	3.1	4.6	6.1	9.2	18.4
MAC payload (1500 Bytes) time	<b>40</b>	<b>44.4</b>	<b>50</b>	<b>66.7</b>	<b>80</b>	<b>88.9</b>	<b>100</b>	<b>133.3</b>	<b>200</b>	<b>266.7</b>	<b>400</b>	<b>800</b>
SIFS	16											
ASK frame time + PHY preamble	28.9	29	29.3	29.6	25.8	26	26.7	28	29.3	32	40	40
Total duration, $T_{cycle}$	<b>210.8</b>	<b>215.5</b>	<b>221.5</b>	<b>234.8</b>	<b>248.6</b>	<b>257.9</b>	<b>270.0</b>	<b>305.4</b>	<b>374.9</b>	<b>445.8</b>	<b>586.2</b>	<b>995.4</b>
Efficiency	19%	21%	23%	28%	32%	34%	37%	44%	53%	60%	68%	80%

The average delays of getting access to the media for the two-station network depending on the data rate of the second station for different performance enhancement techniques are shown in Fig. 2. It is provided that the first station uses the constant data rate  $V_1=300$  Mbit/s.

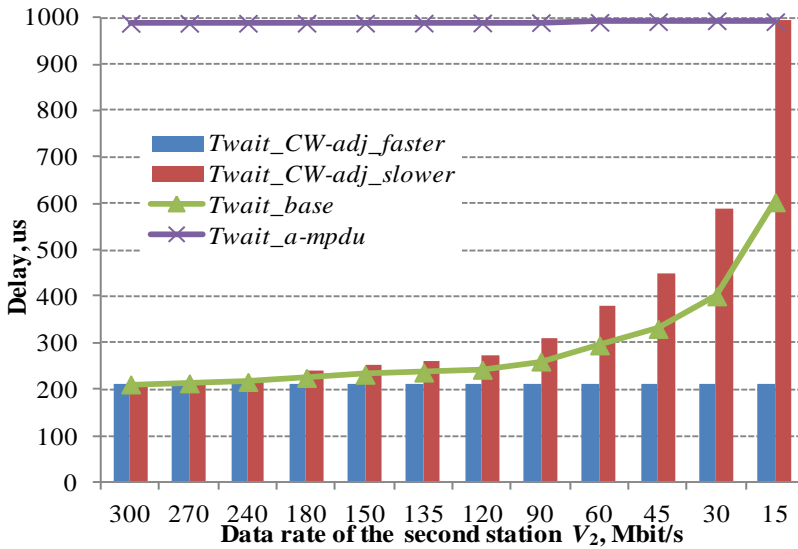
*Twait\_base* – corresponds to the general case when two stations use the standard CW settings ( $CW=15$ ) and the MPDU of the standard Ethernet size (MPDU payload=1500 Bytes). The average delay is equal for both stations as they get equal probabilities of getting access to the media ( $p_i=0.5$ ). Its increase is caused by the fact that the slower station consumes more airtime to send MPDU of the given size at lower data rate.

*Twait\_a-mpdu* – corresponds to the case when the faster station is granted a right to send a frame of a bigger size proportionally to the ratio between stations data rate. It is provided that two stations use the standard CW settings ( $CW=15$ ) and the standard size of MPDU payload (1500 Bytes) is used at the slowest data rate 15 Mbit/s. If station data rate is 300 Mbit/s it uses the A-MPDU payload of 30000 Bytes ( $300/15*1500$ ).

*Twait\_CW-adj\_faster* and *Twait\_CW-adj\_slower* are delays corresponding to faster and slower stations provided that both station use the MPDU of the standard Ethernet size (MPDU payload=1500 Bytes) and the slower station scales up its CW so that stations probabilities of getting access to the media are proportional to the ratio between durations of their transmission cycles.

## 6 CONCLUSIONS

CSMA/CA provides a random multiply access to the wireless medium that means a statistically equal number of chances that each computer get to transfer its data frames over a shared medium. However, different wireless computers can use different data rates depending on a type of their network adapters ( $a/b/g$  or  $n$ ) and also a signal-to-noise ratio. This fact causes the unfairness as slow clients consume more airtime to transfer a given amount of data, leaving less airtime for other clients.



**Figure 2** Average delays of getting access to the media for the two-station network provided that the first station uses the constant data rate  $V_1=300$  Mbit/s

At the same time, high data rate clients spend much more of air time just waiting for an access to the wireless medium than really transferring/receiving data. This decreases the overall network throughput and significantly degrades performance of fast clients.

In the paper we address a problem of such unfairness occurred in multirate Wi-Fi networks. We propose an approach that enables each station to dynamically adapt its contention window so that a fair airtime distribution is provided between all network stations. With this purpose we derived a set of analytical models estimating the size of a fair contention window to be used by slower stations so that both slow and fast stations consume airtime almost equally.

In the theory slower stations should scale up their contention windows depending on a ratio between own data rates and a data rate of the faster station(s). Though, in practice PHY and MAC overheads have to be accounted. This means that fair contention window settings should provide the probability of getting access to the media to be proportional to the ratio between durations of their transmission cycles.

PHY and MAC overheads significantly degrade network effectiveness for high data rate stations. This problem can be solved by implementing A-MPDU or A-MSDU aggregation which is adopted in 802.11n specification. However, frame aggregation approach raises a tradeoff between throughput enhancement [13] and latency increase, discussed in Section 5. Besides, it is hardly applicable for applications like VoIP or instant messaging using short data packets of the order of 100 bytes.

Thus, adaptive frame aggregation and contention window control need to be applied together to effectively increase Wi-Fi throughput and satisfy latency requirements of different applications.

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